

# Status Report On Estimating Historical Radiation Doses To A Cohort Of U.S. Radiologic Technologists

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**Abstract.** This paper presents the current status on an effort to reconstruct occupational radiation doses to about 90,000 U.S. medical radiation technologists. These technologists worked during the years from 1916 through 1984. Since the availability of data useful for reconstructing radiation doses differed by calendar time period, different models were developed for purposes of dose reconstruction for the years before 1960, 1960-1976, and 1977-1984. The dose reconstruction used available film-badge measurements (approximately 350,000) for individual cohort members, information provided by the technologists on their work history and protection practices, and measurement data derived from the literature. The present reconstruction estimates annual and cumulative occupational badge doses (personal dose equivalent) for each technologist for each year worked, as well as absorbed doses to these organs and tissues: bone-marrow, female breast, thyroid, ovary, testes, lung and skin. Assumptions have been made about critical variables including average energy of x rays used in diagnostic examinations, use of protective aprons, position of film badges with respect to the apron, and minimum detectable doses. Uncertainty of badge and organ doses was characterized for each year of each technologist's working career. Monte Carlo methods were used to simulate cumulative organ doses for ongoing cancer risk analyses. Estimates of organ dose (mGy) averaged over the cohort are presented here for purposes of summarizing the present (late-2003) findings: 24 mGy to female breast (n = ~68,000), 6.6 mGy to ovary (n = ~68,000), 40 mGy to testes (n = ~20,000), 11 mGy to lung (n = ~88,000), 62 mGy to thyroid (n = ~88,000), 3 mGy to bone marrow (n = ~88,000), 33 mGy to skin on the trunk of the body (n = ~88,000), and 79 mGy to skin on the head, neck, and arms (n = ~88,000). Maximum estimated dose for most organ/tissue sites was about 60 times the mean value. The models and predictions presented here, while continuing to be modified and improved, represent one of the most comprehensive dose reconstructions undertaken to date for a large cohort of medical radiation workers.

## 1. Introduction

Quantitative dose-response data are limited for populations exposed to chronic fractionated low-to-moderate levels of ionizing radiation. Extrapolation of high doses from Atomic Bomb survivor studies and medically irradiated patients, as well as studies of non-medical nuclear workers have, and will continue to be, the primary sources for understanding the risks from chronic low-level radiation exposure.

Analysis of data derived from the U.S. Radiologic Technologists (USRT) cohort promises to be a significant source of new information on the risk from chronic exposure. The cohort was assembled in the early 1980s using records of the American Registry of Radiologic Technologists, and includes 146,000 technologists certified for at least two years during the period 1926-82 [1]. About 90,000 of this cohort participated in survey in the mid-1980s and are included in this dose reconstruction. This unique cohort is 73% female, with a current median age of about 52 years. Presently, the National Cancer Institute is conducting a retrospective follow-up and assessment of mortality and radiogenic cancer risks among this group [2]. The impetus for the detailed dosimetry described here is to support mortality and cancer risk analyses on data collected on this cohort. Further detail on the dosimetry for this study can be found in Simon *et al.* [3].

Cohort members first worked as radiologic technologists as early as 1916 or as recently as the early 1980s. As expected, the number of years worked and the decade in which a technologist worked greatly influenced his/her cumulative occupational dose received. Technologists who first began working prior to 1940 (n=1,032), during 1940-49 (n=4,236), during 1950-59 (n=12,096), during 1960-69 (n=26,799), during 1970-79 (n=42,358), and during 1980-84 (n=1,252) had worked on average, 25, 22, 17, 14, 9, and 4 years, respectively, by the mid-1980s when the baseline questionnaire was administered. The calendar years in which USRT members worked spanned the development of modern-day radiology during which exposure to occupational radiation declined dramatically.

## **2. Methods**

### **2.1 Overview and Objectives**

The goal of the dose assessment has been to create a year-by-year record of badge and organ doses, with estimates of the uncertainty on each annual dose, for each individual cohort member and to use those data for estimating cumulative (i.e., professional lifetime) badge and organ doses. In this study, both the annual and cumulative doses are expressed in the form of probability (i.e., uncertainty) density functions (pdf) for each individual. Each pdf represented the range and likelihoods of plausible doses for the true annual dose or for the true cumulative dose.

Because the availability and quality of badge dose data differed during different time periods, we developed three different dose estimation methods, one for each of three time periods: the years prior to 1960, 1960 through 1976, and 1977 through 1984. Over 17,000 cohort members (12% of the total cohort) began work prior to 1960, when occupational exposures to ionizing radiation were highest. The pre-1960 period represents about 11% of the person-years worked; the period from 1960 through 1976 represents about 49% of the person-years worked; and the time period from 1977 through 1984 represents about 40% of the total person-years worked. Overall, only about 30% of the person-years had film-badge measurements; hence, a majority of annual exposures had to be estimated.

### **2.2 Estimation of Badge Doses: Brief Summary of Methods**

The data available for reconstruction of badge doses within the three time periods varied considerably in quantity and quality. The methods we used to reconstruction doses within each period are briefly described in the following paragraphs and summarized in Table 1.

#### **2.2.1 Pre-1960 Period**

The estimates of annual doses for individual cohort members before 1960 are based on a synthesis of data from literature reports of personnel badge dose and other (e.g., scatter) measurements and the recommended national radiation protection standards at the time. We identified eleven publications providing quantitative film badge measurement data for the pre-1960 period; one of these provided exposure information for the period before 1940, four for the years 1940-1949, and six for the years 1950-1959 [3].

Empirical distributions of badge doses were developed for 10-year periods primarily because the sparse literature data did not allow us to discern changes in doses received within shorter periods. The period before 1940 is particularly problematic as almost no reliable information has been located. Presently, the dose distribution for each decade before 1940 is taken to be that of the 1930-1939 distribution.

To derive decade-specific distributions, we first evaluated the film badge data presented in the eleven publications for the decades to which they applied. Many of the publications required a degree of interpretation of the reported badge measurements, because key variables (e.g., number of persons monitored or monitoring frequency) were often not explicitly stated. Using all available information,

we derived a frequency distribution of film badge readings from each publication taking into account the time interval over which monitoring was conducted, and the monitoring frequency.

Table 1. Badge dose estimation by time period: summary of cohort size, sources of data, and estimation methods

Pre-1960	1960-1976	1977-1984
<i>Number of technologists that began working in period<sup>a</sup>:</i>		
17,364	58,911	11,498
<i>Person-years worked:</i>		
108,070	495,371	411,693
<i>Sources of dosimetry data:</i>		
Film measurements and badge dose data from the literature.	Limited annual badge dose data from cohort members.	More than 350,000 badge dose measurements of cohort members.
<i>Dose estimation methods:</i>		
Data from publications are weighted by applicability to cohort and aggregated.	Uses the same annual parent badge dose distribution for all years in period.	Uses loglinear predictive model when individual annual badge dose data are not available.
Annual dose distributions developed for 3 subperiods (<1940, 1940-1949, 1950-1959).	Individual doses are selected at random from the hospital or physician's office parent distribution.	Individual doses are selected at random from the statistical model's distribution or from the badge dose measurement error distribution.
Individual doses are selected at random from the subperiod parent distribution by Monte Carlo simulation.		

<sup>a</sup>2,532 of 90,305 cohort member were eligible to work as a radiologic technologist, but never did.

Though the simplest approach would have been to pool all the badge measurements by decade, that would assume that the proportions of badge doses represented by each publication were in the same proportions as the doses received by the entire cohort. That assumption was found to be inaccurate since, in some cases, academic, and presumably, better protected hospitals, published much more data. Consequently, we assigned a weighting factor to each publication with an uncertainty of the weighting factor expressed as a uniform pdf.

A Monte Carlo simulation was then performed, sampling the weights for each publication and generating global pdfs within each decade for each trial. The procedure was repeated thirty times and the means and variances were averaged over the 30 trials, within each decade.

### 2.2.2 1960-1977 Period

In this time period, a small number of available cohort badge readings were used to develop a simple exposure model. For our purposes, we estimated a separate lognormal distribution of badges doses for the populations working in hospitals and physician's offices, since available information indicates that exposures differed among the two types of working environments.

Data were obtained from two sources: (a) microfilm reels containing dosimetry reports of Landauer, Inc.; and (b) a survey of radiologic technologist employers. The badge readings represented about 560

individuals; they were treated as independent measurements and pooled to determine the average dose within the time period. During this period, we restricted our analysis to the approximate 500 badge readings that were known to be taken on the outside of a protective apron. The data indicated nearly the same average annual badge dose for each year during this period. Therefore, we used a single pdf to represent the population of badge doses for each year within the period of 1960 through 1977. Note that the dose assigned to each subject in each year of this period was selected at random by Monte Carlo sampling from this parent distribution.

In using the available film badge data, the issues of reported zero annual doses, and very low annual doses that reflected the minimal detectable limits, had to be addressed. To estimate the distribution mean and variance taking into account the minimum detectable dose, we used maximum likelihood estimation, with the likelihood function including a cumulative lognormal density function (CDF) to account for the values that were potentially under-reported. Thus, the likelihood function also has terms of  $CDF(D)$ , where we assume the true dose is less than or equal to  $D$ .

The likelihood function is then:

$$L(d_1, d_2, \dots, d_k, d_{k+1}, \dots, d_n; \mu; \sigma) = \prod_{i=1}^k f(d_i, \mu; \sigma) \prod_{i=k+1}^n CDF(d_i; \mu; \sigma) \quad (1)$$

where the  $d_i, i \leq k$  are the reported doses, and  $d_i, i > k$  is a bounding dose where the true dose, because of minimal detectable limits is less than or equal to  $d_i, i > k$ . The likelihood function (eq. 1) was maximized to obtain estimates for the overall mean and variance of a dose pdf for a single year. This pdf was applied for every year during the period 1960-1976.

### 2.2.3 1977-1984 Period

In contrast to the two earlier periods, the dose estimation method for 1977-1984 relied heavily on personnel monitoring records from Landauer, Inc. For 1977-1994, approximately 350,000 annual badge readings were obtained for cohort members from the computerized records of Landauer. The 350,000 measured badge doses were used in conjunction with information on work history obtained from each subject to develop a general linear model to predict the annual badge dose for cohort members without measurements. The actual badge measurement was placed in an individual's year-by-year dosimetry record when available; otherwise, the dose was predicted by the model described here.

The predictive model we developed is a generalization of :

$$\ln(\text{Dose}_j) = \Xi_1 X_{j1} + \Xi_2 X_{j2} + \dots + \Xi_k X_{jk} + \epsilon_j \quad (2)$$

where the  $\Xi_i$  ( $i=1$  to  $k$ ) denote the fixed effects parameters to be estimated, and  $j$  runs over the set of observed doses. However, because repeated measures are taken on the same subject over time, and these repeated measures are correlated, an additional correlation structure was imposed.

Predictor variables in the multivariate model included: the frequency of performing specific radiologic procedures (e.g., fluoroscopy, nuclear medicine); the type of facility where the technologist worked (hospital or physician's office); the frequency of using protective measures (e.g., lead apron use); the technologist's use of certain practices (e.g., holding patients during x rays); and the technologist's sex and age in 1984 when a baseline questionnaire was administered. To take into account the correlation of annual doses over time for a given subject, the significant predictor variables were modeled further, using a repeated measures approach.

To establish an uncertainty pdf for each subject, we used one of two methods. First, when an actual badge dose reading was available from Landauer, the uncertainty was viewed as deriving solely from laboratory measurement error inherent in film-based dosimetry. For that case, a lognormal pdf with a geometric standard deviation (GSD) of 1.2 was assumed, the rationale being that a measurement error

of one standard deviation (or more precisely the 85<sup>th</sup> percentile of the lognormal uncertainty distribution) could result in a measurement being as much as 20% higher. For doses predicted by the statistical model, the uncertainty pdf was derived from the total modeling error, which, in turn, was considered to be the sum of two errors, a propagation of errors term and the residual error, yielding a GSD of 2.32.

## 2.3 Estimation of Organ Doses

### 2.3.1 Dose factors

Organ doses were estimated from measured or estimated film badge measurements, assessed today for regulatory purposes in the U.S. as *personal dose equivalent* (mrem or mSv). In this work, we use the term *film badge dose* in lieu of *personal dose equivalent*, primarily because the USRT study period includes decades (i.e., before 1960s) when film badge measurements primarily represented a measure of air ionization (Roentgens) as well as later times when the terms *deep dose*, *dose equivalent*, and *personal dose equivalent* were used.

In this study, estimation of organ doses involves the use of measured or estimated film badge readings and dose factors developed from data provided by the International Commission on Radiological Protection [4]: 1)  $D_T/K_a$ , the organ absorbed dose per unit of air kerma free-in-air (Gy per Gy), and 2)  $H_p(d)/K_a$ , the personal dose equivalent per unit of air kerma free-in air (Sv per Gy). Table 2 presents the dose factors used for estimating organ doses, based on measured or predicted film badge readings. Presently, we do not have information to determine the proportions of the total exposure received by individual technologists from different types of radiation sources and/or sources of different energies. Given such information, it might be possible to partition the total dose into different energy fractions, each with a different dose factor. Presently, however, only dose factors for 35 keV are used. That energy was chosen because it is close to the predominant energy of most diagnostic x ray machine emissions.

Table 2. Tissue and organ dose factors in Gy per Sv at 35 keV, derived from [4]

Organ or Tissue	d (mm)	$\frac{D_T}{K_a} / \frac{H_p(d)}{K_a}$ [Gy/Sv]
red bone marrow	10	0.10
female breast	10	0.87
thyroid	10	0.87
ovary	10	0.24
testes	10	0.99
lung	10	0.37
skin	0.07	1.1 <sup>a</sup>

<sup>a</sup>The value of  $D_T/K_a$  for skin is multiplied by 2 because ICRP [4] averages the energy fluence over the entire skin surface. In this study, the back of the body is assumed not to be exposed. This value applies to areas of skin that faced the source of radiation (e.g., front of face); for areas of the skin that faced away from the source of radiation (e.g., back of the trunk), the value was approximated as zero.

### 2.3.2 Accounting for protective apron usage

Badge dose estimates must be adjusted for use of protective aprons and for placement of the badge relative to the apron so that the organ absorbed properly reflect the shielding afforded by protective

aprons when they were worn. The data collected from a questionnaire administered to the cohort allowed us to formulate a discrete-valued probability function describing the likelihood of apron protection for each individual, for each year worked. The probability function for apron usage was defined for each year by probabilities of three mutually exclusive events: 1) did not wear an apron; 2) wore an apron and a badge outside of apron; 3) wore an apron and a badge under apron. Let  $P_{NoA}$ ,  $P_{AO}$ , and  $P_{AU}$  denote the probabilities for those respective events. Thus, the discrete ‘probability-of-protection’ function,  $P_{Protection}$ , can be described as:

$$P_{Protection} = \begin{cases} P_{NoA} & \text{(probability of no apron)} \\ P_{AO} & \text{(probability of badge outside the apron)} \\ P_{AU} & \text{(probability of badge under the apron)} \end{cases} \quad (3)$$

For each individual, the values of  $P_{NoA}$ ,  $P_{AO}$ , and  $P_{AU}$ , were based on their responses to a questionnaire administered in the mid-1980s. The questions concerning apron usage were not specific to particular years the technician worked; instead, they inquired about the use of protective aprons when he/she first began working and at the time of the questionnaire. For those individuals who stated they wore an apron when they first began working as well as at the time of the questionnaire, and for those who indicated they did not wear an apron at either time, we assumed the same response for the intervening years. The discrete probability distribution (eq. 3) was applied to those cases where the individual gave a mixed response (e.g., “no” when first starting and “yes” at the time of the questionnaire). In that case, we found the likelihood of wearing an apron in a given year from data on apron usage in specific years derived from the entire cohort.

### 2.3.3 Computation of Organ Doses

For a specific individual in a given year, each organ dose is derived from the badge dose for that year (either a measured or predicted value), the organ dose factor (Table 2), the probability of protection value for that year, and the apron attenuation factor. Two equations are used, depending on whether the organ is covered by the apron or not:

Organs/tissues under apron (i.e., red bone marrow, breast, lung, ovary, testis, skin of trunk)

$$\text{Organ dose (mGy/yr)} = BD_{m,sim} \times DF_o \times [P_{NoA} + AAF \times P_{AO} + P_{AU}] \quad (4)$$

Organs/tissues outside apron (i.e., thyroid, skin of head/neck, and arms)

$$\text{Organ dose (mGy/yr)} = BD_{m,sim} \times DF_o \times [P_{NoA} + P_{AO} + (1/AAF) \times P_{AU}] \quad (5)$$

where,

$BD_{m,sim}$  = badge dose (either measured or simulated)

$DF_o$  = dose factor for a specific organ,

$P_{NoA}$ ,  $P_{AO}$ , and  $P_{AU}$  = the probabilities for not wearing an apron, wearing an apron with the badge outside, and wearing an apron with the badge underneath, respectively,

$AAF$  = apron attenuation factor, taken as 0.4 (Note: As presented below, we assumed a protective apron attenuates the exposure by 80%; however our survey asked if the individual “usually wore an apron.” We interpreted that to mean an apron was worn approximately 75% of the time. It follows that  $AAF = [(0.2 \times 0.75) + (1 \times 0.25)] = 0.4$ ).

Apron attenuation, or the reduction in dose afforded by a protective lead apron, is a function of its thickness and the incident energy. Typical thicknesses for lead aprons have been 0.25 mm and 0.5 mm Pb equivalent. For x-ray beams of 70 kVp, 100 kVp, and 120 kVp, calculations and measurements show that lead aprons of 0.5 mm will result in a reduction in exposure of 99%, 97%, and 95%, respectively [5,6]. In this study, we assumed an 80% reduction in exposure beneath the apron to account for three possibilities: 1) some aprons worn were thinner than 0.5 mm Pb, 2) scattered radiation results in some exposure to parts of the body unshielded by the apron, and 3) some energies,

particularly from radioisotopes, were higher than we assumed for diagnostic radiology practices. Our assumption of 20% transmission is in agreement with those of McGuire *et al.* [7] who studied exposures of personnel performing fluoroscopy. In some cases, however, we realize that aprons would be more protective than estimated.

### 2.3.4 Uncertainty and Dose Estimation: Simulation, Correction for Bias, and Correlation

The dosimetry for each individual, as noted previously, produced a year-by-year lognormal pdf of badge dose and associated organ doses. To obtain realizations of cumulative dose for each individual, Monte Carlo simulation was used. Furthermore, we attempted to account for potential bias in each lognormal pdf by introducing an uncertainty distribution in each pdf's mean value. In addition,, because an individual's yearly dose is correlated with the subsequent year's dose, we introduced a temporal correlation. The method to induce temporal correlation in the simulation was the rank correlation method developed by Iman and Conover [8].

## 3. Findings

For each of the 87,744 technologists who worked for at least one year during the period 1916-1984, the dose assessment developed a badge dose (mSv) pdf for each year worked, as well as a cumulative (professional lifetime) pdf of the absorbed dose (mGy) to eight different organs and tissues. Organs and tissues for which doses were estimated included red bone-marrow, female breast, thyroid, ovary, testes, lung, and skin. The Tables 3, 4 and 5 summarize some of the dose-related findings to date.

Table 3 presents the population mean, median and GSD of annual estimated badge dose distributions (mSv) for the cohort of technologists by time period and type of facility prior to 1976. The estimated population mean badge dose declined more than 40-fold, from 100 mSv per year from before 1940 to about 2.3 mSv per year during 1977-1984. The overall population mean badge dose for hospital workers declined about 75% from the 1930s to the decades of the 1940s and 1950s. There was another 80% decline in the annual dose from about 28 mSv (on average) in the 1950s to about 3.6 mSv during the 1960-1976 period.

Table3. Summary of annual uncertainty distributions of badge dose (mSv) for USRT study assigned to each cohort member

Calendar period	Facility type	Median	Mean	GSD
$\leq 1939$	Hospital	71	100	2.4
$\leq 1939$	Physician's office	54	80	2.4
1940 - 1949	Hospital	16	25	2.5
1940 - 1949	Physician's office	13	19	2.5
1950 - 1959	Hospital	11	28	3.9
1950 - 1959	Physician's office	8.6	22	3.9
1960 - 1976	Hospital	2.2	3.6	2.7
1960 - 1976	Physician's office	1.6	2.6	2.7

Table 4 presents population summary statistics for mean organ doses (mGy) during the time period 1916 through 1984. Note that the population mean is an average of the individual mean cumulative dose for each subject included in the category. Here, each subject's cumulative mean dose is simply a sum of their annual mean organ dose over the years they worked. The numbers of estimated doses to the female breast, ovary, and testes reflect the cohort proportions of about 77% female and 23% male. The population mean dose for each specific organ/tissue varies with the depth of the organ within the body and the proportion of technologists who wore protective aprons. In general, the skin of the head, neck and arms was estimated to have received the highest cumulative dose (about 80 mGy, on average). The thyroid received the next highest cumulative dose (62 mGy), followed by the testes (40

mGy), skin on the trunk (33 mGy), female breast (24 mGy), lung (11 mGy), ovary (6.6 mGy), and red bone marrow (3 mGy). The population coefficients of variation ( $CV = \sigma / \bar{x}$ ) for most organs/tissues were similar, ~1.7 to 2.0.

Table 4. Summary statistics on estimated cumulative mean organ doses (mGy) over all years worked (1916-1984); summary statistics are for non-zero values only

	Female breast dose (mGy)	Ovary dose (mGy)	Testes dose (mGy)	Lung dose (mGy)	Thyroid dose (mGy)	Red bone marrow (mGy)	Skin dose: trunk (mGy)	Skin dose: head, neck, arms (mGy)
Number	67,736	67,724	20,008	87,742	87,744	87,652	87,744	87,744
Minimum	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.2
Maximum	1,900	530	2,020	820	2300	220	2,400	2,900
Median	12	3.4	19	5.5	31	1.5	16	40
Mean	24	6.6	40	11	62	3	33	79
SD*	47	13	67	21	105	5.8	64	130
CV**	2.0	2.0	1.7	1.9	1.7	1.9	1.9	1.6

\*Standard deviation, \*\* Coefficient of variation =  $\sigma / \bar{x}$

Uncertainty on organ doses for individuals was determined from 100 simulated values of cumulative (professional lifetime) dose for each subject. For example, the mean GSD for cumulative breast dose was about 3.0, though it ranged for different individuals from 1.7 to 4.4. Uncertainty on other organ doses would have been of similar magnitude.

Table 5 summarizes estimates of cumulative mean breast dose (mGy) for female technologists according to the decade in which they began working. As expected, the cumulative mean breast dose decreased over time with the most dramatic changes, in absolute terms, taking place during the earlier decades. Between 1916-39 and 1940-49, the estimated cumulative dose to the breast fell from 320 mGy on average to 98 mGy on average; thereafter the mean dose declined by 50% or more between the years 1940-49 and 1950-59 and between 1950-59 and 1960-69. The declines in mean average dose were smaller between 1960-69 and 1970-79 and between 1970-79 and 1980-89.

Table 5. Summary statistics on estimated cumulative mean female breast dose (mGy) by decade first worked.

	1916-1939	1940-1949	1950-1959	1960-1969	1970-1979	1980-1984
Number of female technologists	792	2,769	9,144	21,391	32,634	1,025
Minimum	7.3	1.9	1.3	0.1	0.1	0.2
Maximum	1,900	410	370	130	180	36
Median	260	94	44	14	9.0	3.2
Mean	320	98	49	15	10	4.0
SD	220	50	26	9.1	7.5	3.4
CV	0.69	0.51	0.53	0.61	0.75	0.50

## 4. Discussion

For the first time, both annual and cumulative occupationally-received individual radiation doses have been estimated for eight specific organs and tissues for a large group of radiologic technologists working in the U.S. since the early decades of the twentieth century until the mid-1980s. All doses are described from the dose reconstruction as uncertainty distributions, rather than only as point estimates.

A number of previous suppositions about exposures of medical personnel are supported by our findings. In particular, the population average equivalent dose to technologists (represented by badge doses) has declined over the decades of radiologic practice. Doses during the 1960's and most of the 1970's were quite constant similar to the situation in the United Kingdom where there was little variation observed between 1960 and 1965 [9]. By the mid-1980s, average annual doses appeared to be only a very small fraction of those received prior to 1940.

The dose reconstruction also indicates substantial differences in organ doses that would not otherwise be obvious from film-badge measurements alone. Superficial organs and tissues, e.g., thyroid, testes, female breast, and skin of the head and neck region received, on average, similar estimated cumulative doses, which were among the highest of all organs assessed. More deeply-seated organs, e.g., the ovary, lung, and even more so, the red bone marrow, received cumulative doses that were less than doses received by the more superficial organs. Thus, our efforts to estimate organ doses should make estimates of radiogenic cancer risks more definitive than studies relying solely on film-badge measurements.

## 5. Concluding Remarks

We are continuing to refine the dose reconstruction, primarily by acquiring more data, with an emphasis on the earlier years that technologists worked. One aim is to reduce the uncertainty in each individual's annual dose pdf by partitioning the population pdfs for the early decades into smaller-ranged variance pdfs, and by applying those to individuals who either likely received very high or very low doses compared to others in the cohort. Information from an ongoing cohort survey (in 2004) will provide further detailed information on types and frequency of radiologic procedures performed, as well as detailed information on protection practices, by year. Our efforts to acquire more cohort-specific monitoring data will concentrate on those cohort members that worked in the military services and in sentinel hospitals that employed large numbers of technologists. Given the size of the USRT cohort, the number of specific organs/tissues considered, the development of year-by-year uncertainty distributions, and the generation of multiple realizations of organ doses, this study is the most comprehensive dose reconstruction for radiologic personnel to date.

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